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Satellite-based assessment of cloud-free net radiative effect of dust aerosols over the Atlantic Ocean

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[1] Using eighteen months (June–August, 2000–2005) of spatially and temporally collocated Moderate Resolution Imaging Spectroradiometer (MODIS) and the Clouds and the Earth's Radiant Energy System (CERES) data from the Terra satellite over the Atlantic Ocean [10W–60W, 0–30N], we first separate the dust aerosol optical thickness at 0.55 μm (AOT) from the total column MODIS AOT. We then calculate the cloud-free TOA net radiative effect (NRE) of dust aerosols by accounting for diurnal effects and sample biases. The cloud-free NRE is -6.31 ± 1.16 Wm^{-2} and nearly twenty percent of the shortwave radiative effect (-7.75 ± 0.86 Wm^{-2}) is cancelled by the longwave radiative effect ($+1.44 \pm 0.57$ Wm^{-2}) indicating the importance of the dust aerosols in the thermal portion of the electromagnetic spectrum. This is the first multi-year satellite-based assessment of the NRE of dust aerosols indicating the importance of *both* the shortwave and longwave radiative effects of dust aerosols over the oceans unlike anthropogenic aerosols that have negligible TOA longwave radiative forcing effects. **Citation:** Christopher, S. A., and T. Jones (2007), Satellite-based assessment of cloud-free net radiative effect of dust aerosols over the Atlantic Ocean, *Geophys. Res. Lett.*, *34*, L02810, doi:10.1029/2006GL027783.

1. Introduction

[2] Worldwide annual dust aerosol emissions can range from 1000–3000 Tg and are major contributors to the radiation balance of the earth-atmosphere system [*Cakmur et al.*, 2006]. They are effective in scattering and absorbing incoming solar radiation [*Haywood et al.*, 2003] and have significant effects in the longwave portion of the electromagnetic spectrum since they have large particle sizes and emit at a colder temperature when compared to clear sky regions [*Zhang and Christopher*, 2003]. Desert dust is considered to originate mainly from natural sources [e.g., *Tegen et al.*, 2004] although large uncertainties exist in determining the contribution of land use or anthropogenic sources to dust loading [*Mahowald et al.*, 2004].

[3] The difference between the top of atmosphere (TOA) clear sky and dust aerosol regions is called the dust radiative effect (DRE) that is an important parameter for climate studies. Over open oceans, where surface albedos are low, dust aerosols increase the reflectivity of the earth-atmosphere system thereby making TOA shortwave radiative effect (SWRE) negative in sign. On the other hand, since dust aerosols emit at colder temperatures, the sign of the longwave radiative effect (LWRE) is positive [*Zhang and Christopher*, 2003]. The Net Radiative Effect (NRE) is the sum of the SWRE and the LWRE. Anthropogenic aerosols on the other hand have smaller particle sizes and therefore have negligible effects in the longwave.

[4] Most assessments of the DRE are largely from numerical modelling simulations [e.g., *Miller et al.*, 2006]. In these studies, dust concentrations are based on the distributions of vegetation, soil texture and soil moisture. The mass concentrations are converted to aerosol optical thickness (AOT) values and DRE is obtained using radiative transfer calculations that require wavelength dependent aerosol properties. However, large uncertainties exist even in the sign of the DRE [*Myhre and Stordal*, 2001]. Alternatively some studies use satellite-retrieved AOT and radiative transfer calculations to convert the spectral optical thickness to obtain the radiative effect of all aerosols over the entire shortwave spectrum [e.g., *Remer and Kaufman*, 2005] while others combine the satellite-retrieved AOT with broadband radiative flux measurements to examine the DRE of all aerosols that do not require radiative transfer calculations [e.g., *Zhang et al.*, 2005b].

[5] Recently, *Li et al.* [2004] use MODIS level 2 AOT data and the CERES ERBE like product (ES-8) data over the Atlantic Ocean and assuming that the total column AOT during June–August is only due to dust aerosols, they reported the shortwave radiative efficiency (DRE/optical depth) of aerosols over the Atlantic Ocean to be -35 ± 3 W m^{-2}. They do not calculate the longwave effects of dust aerosols. However multi-year spatially and temporally collocated CERES and MODIS data now exists called the CERES Single Satellite Footprint (SSF) with high quality angular models [*Zhang et al.*, 2005a] that are more suited for aerosol research. For example, *Loeb and Kato* [2002] report that the uncertainties in CERES SSF TOA fluxes are 3–5 times smaller when compared to the ES-8 CERES data products.

[6] New techniques also exist to separate the total column AOT into dust, anthropogenic and marine components [*Bellouin et al.*, 2005; *Kaufman et al.*, 2005]. Instead of assuming that all aerosols over the region of study during June–August are due to dust aerosols alone, we use the methods described by *Kaufman et al.* [2005] to separate dust AOT from the total column MODIS AOT at 0.55 μm and then use broadband CERES measurements coupled with specific angular models [*Zhang et al.*, 2005a] to estimate DRE of dust aerosols. We account for diurnal variations using methods described by *Remer and Kaufman* [2005], and since the CERES footprint is much larger than the MODIS, we adjust for sample biases using a modified approach that was originally described by *Zhang et al.*

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[2005b]. The major goal of this paper is to combine multi-year CERES/MODIS measurements to separate the dust portion of the total AOT and to examine *both* the TOA shortwave and the longwave radiative effect to determine the NRE of dust aerosols.

2. Methods and Results

[7] We use 18 months of the CERES Single Satellite Footprint (SSF) data [June–August, 2000–2005] over the Atlantic Ocean [10W–60W, 0–30N]. This region is downwind of one the largest sources of dust aerosols from Africa with the highest dust emissions during the Northern hemisphere summer months [*Prospero et al.*, 2002]. The CERES SSF product contains the point spread function weighted MODIS aerosol and cloud properties for each CERES footprint. The CERES reports measured TOA radiances and they are inverted to fluxes using angular dependence models (ADM's). We use the Terra ADM's derived by *Zhang et al.* [2005a] that are a function of AOT, surface wind speed and fine mode fraction.

[8] To derive the dust portion of the total TOA DRE, we use the method developed by *Kaufman et al.* [2005] (equations (1)–(5) below) to separate MODIS AOT ($\tau_{0.55}$) into three components including maritime sea spray (τ_{ma}), atmospheric dust (τ_{du}), and anthropogenic aerosols (τ_{an}) (equation (1)).

$$\tau_{0.55} = \tau_{ma} + \tau_{an} + \tau_{du} \tag{1}$$

The maritime contribution is estimated using surface wind speed (W) derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) that is reported within the CERES SSF product. (equation (2)).

$$\tau_{ma} = 0.007W\left(ms^{-1}\right) + 0.02 \tag{2}$$

The MODIS total fine mode fraction (f) is defined as the ratio of fine- mode optical thickness to the total AOT, and can be separated into the same three components where f_{ma}, f_{du}, and f_{an} correspond to the fine mode fraction of maritime, dust, anthropogenic aerosols respectively (equation (3)).

$$f = [f_{ma}\tau_{ma} + f_{du}\tau_{du} + f_{an}\tau_{an}]/\tau_{0.55} \tag{3}$$

Over oceans, the MODIS uses six spectral bands between 550–2100 nm to retrieve aerosol information by fitting a look up table (LUT). The LUT contains both the fine (effective radii, 0.1–0.25 μm) and coarse aerosols (1–2.5 μm). In the retrieval, the best fitting fine and coarse aerosol models are chosen and the AOT at 0.55 μm along with the fine mode fraction are retrieved [*Kaufman et al.*, 2005]. Dust AOT can then be derived by combining equations (1)–(3) and solving for τ_{du} (equation (4)) using the assumption that f is bounded by: ($f_{\mathrm{ma}} \leq f \leq f_{\mathrm{an}}$).

$$\tau_{du} = [\tau_{0.55}(f_{an} - f) - \tau_{ma}(f_{an} - f_{ma})]/(f_{an} - f_{du}) \tag{4}$$

[9] To calculate τ_{du}, values for f_{ma}, f_{du}, and f_{an} are required. *Kaufman et al.* [2005] estimated these values for the tropical southern Atlantic (0–30°S) resulting in equation (5), and they report an error 10–15% in the retrieved dust AOT.

$$f_{ma} = 0.3 \pm 0.1,\ f_{du} = 0.5 \pm 0.05,\ f_{an} = 0.9 \pm 0.05 \tag{5}$$

[10] The DRE is calculated by subtracting CERES SW or LW flux where dust aerosols are present from clear-sky flux. Clear-sky (cloud *and* aerosol-free) regions are defined as areas where the percentage of a CERES pixel covered by clouds *and* the separately measured MODIS cloud fraction are both ≤1% (for viewing and zenith solar angles less then 60°). Clear sky flux, denoted as F_{clr}, is calculated on a pixel-by-pixel basis by assuming that a linear relationship exists between AOT and TOA flux for $\tau_{0.55} < 0.2$ for 10° solar zenith angle bins and by subtracting the AOT* slope values from the CERES fluxes [*Zhang et al.*, 2005a]. The mean SW and LW clear-sky flux values for the region of study over all six years are 76.09 ± 0.80 and 289.81 ± 1.35 Wm^{-2} respectively.

[11] To calculate the DRE, the CERES instantaneous flux is scaled according to the proportion of AOT made up by dust aerosols (τ_{du}) using equation (6).

$$DRE = \frac{\tau_{du}}{(\tau_{0.55} - \tau_{ma})} \times (F_{clr} - F_{aero}) \tag{6}$$

[12] F_{aero} denotes the TOA fluxes for non-aerosol free pixels that are identified using equations (1)–(5). Equation (6) indicates that the same fraction between dust and anthropogenic components from MODIS data is applied to the CERES fluxes and is based on the near linear relationship between MODIS AOT and CERES fluxes for the range of AOT used in this study [*Christopher et al.*, 2006] and is valid to within 4–5%. The Instantaneous DRE at the time of the satellite overpass is calculated on a pixel-by-pixel basis and diurnally averaged values based on *Remer and Kaufman* [2005]. However, the diurnally averaged DRE from this method is biased towards clear skies, since the CERES footprint is much larger than the MODIS. To account for this bias, we use a modified version of the approach used by *Zhang et al.* [2005b]. We first calculated dust AOT using the *Kaufman et al.* [2005] technique separately from a) the MODIS aerosol product and, b) the MODIS AOT reported within the CERES footprint from the CERES-SSF product. For each CERES level pixel, the dust AOT difference between CERES-SSF AOT and the nearest MODIS dust AOT is calculated. The dust AOT difference between the MODIS and CERES products is averaged for all CERES pixels resulting in an overall value of 0.046 indicating that studies that utilize CERES data must account for this bias. This number represents the magnitude of the bias and is multiplied by the diurnally averaged SW and LW efficiency to form the bias adjustment. Note that we used only the dust SW and LW efficiency in this adjustment and do not assume that all aerosols have the same efficiency. Diurnally averaged DRE values are then added to produce final bias-adjusted values [*Zhang et al.*, 2005b].

[13] Figures 1a–1d show the six-year (June–August) mean dust AOT, longwave, shortwave, and the NRE of dust aerosols and relevant statistics are shown in Table 1. Dust aerosols contribute over 60% to the total MODIS AOT. The SWRE, LWRE and NRE values have been

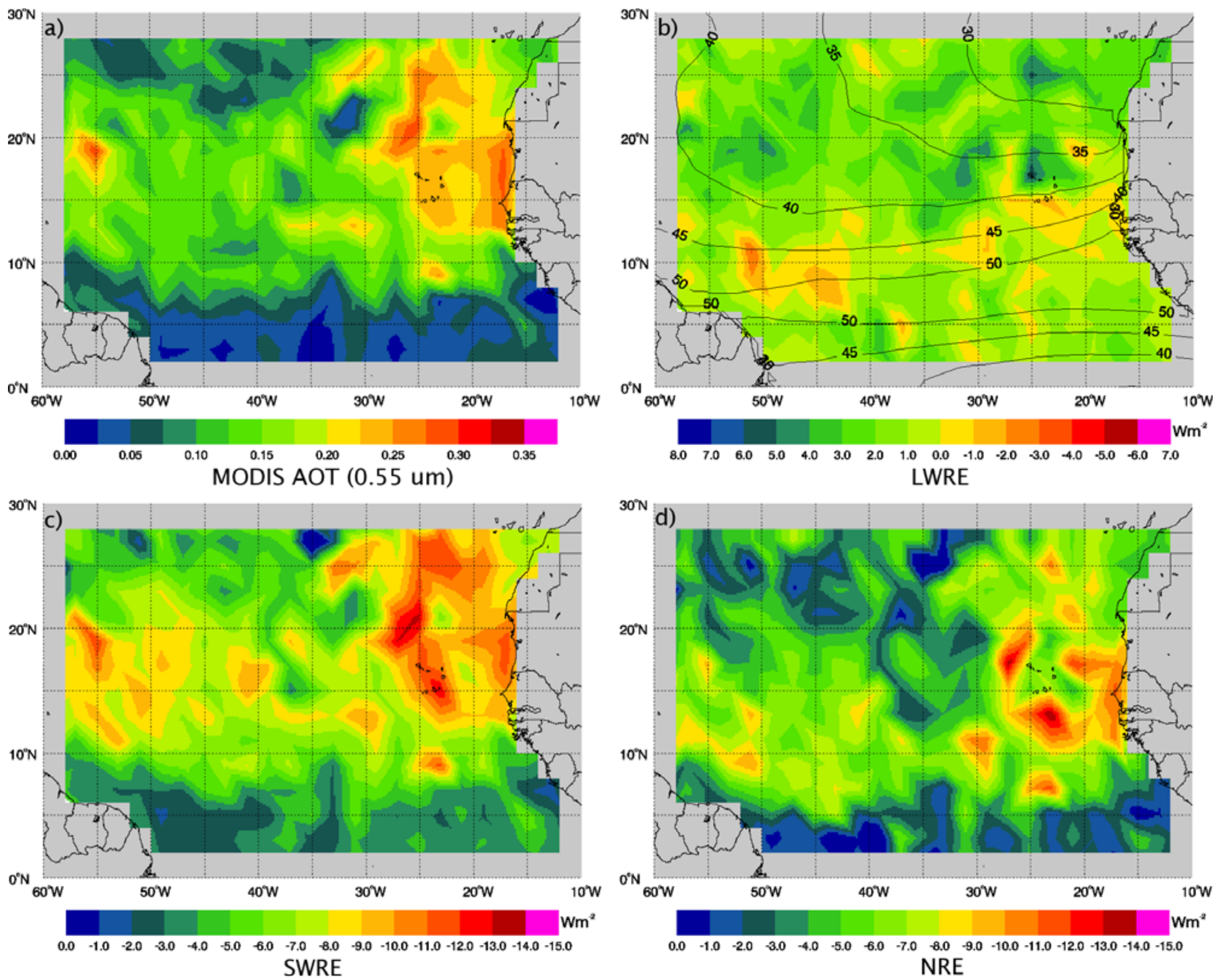

Figure 1. Six year mean of (a) dust aerosol optical thickness, (b) top of atmosphere Longwave radiative effect (LWRE) with contours of total column water vapor in mm from the Special Sensor Microwave Imager (SSM/I), (c) Shortwave Radiative Effect (SWRE), and (d) Net Radiative Effect (NRE) from combined MODIS/CERES measurements.

corrected for diurnal effects and sample biases. Figure 1a shows that the greatest concentration of dust aerosols lie just west of the African coast, between 30–15°W that is consistent with previous studies [*Prospero et al.*, 2002]. Figure 1b shows the large SWRE that dust aerosols exert on the TOA radiation balance. Peak SWRE values are -15 Wm^{-2} in the tropical east Atlantic Ocean, which corresponds well to the greatest concentration of dust aerosols. The SWRE decreases to about half its value in the western Atlantic. Figure 1c shows the corresponding LWRE values with contours of total column water vapor in mm from the Special Sensor Microwave Imager (SSM/I). The LWRE effect is nearly five to six times smaller in the Eastern Atlantic Ocean with isolated high values (e.g. 10N, 50W). The low value of LWRE indicates that *on the average*, their emitting temperature is probably close to that of the surface. There is no apparent correlation (not shown) between regions of high LWRE and water vapor indicating

Table 1. Relevant Statistics for Top of Atmosphere Dust Radiative Effects for June–August From 2000–2005 From Terra for the Region 10W–60W, 0–30N[a]

	2000	2001	2002	2003	2004	2005	Mean ± STD
Total MODIS AOT	0.31	0.27	0.29	0.29	0.31	0.27	0.29 ± 0.02
Total CERES AOT	0.23	0.26	0.24	0.22	0.26	0.22	0.24 ± 0.02
Dust AOT	0.17	0.17	0.16	0.16	0.17	0.14	0.16 ± 0.01
SWRE (Wm^{-2})	−8.41	−8.20	−6.72	−8.59	−7.94	−6.63	−7.75 ± 0.86
LWRE (Wm^{-2})	1.87	0.44	1.71	1.13	1.94	1.54	1.44 ± 0.57
NRE (Wm^{-2})	−6.54	−7.76	−5.01	−7.46	−6.01	−5.09	−6.31 ± 1.16

[a]All DRE values are diurnal averages corrected for sampling biases. All MODIS AOT values are reported at 0.55 μm. The SWRE and LWRE are the top of atmosphere shortwave and longwave radiative effects while the NRE is the sum of SWRE and LWRE.

that the LWRE is largely from dust aerosols. The resulting NRE shown in Figure 1d shows the dominating effect of the SWRE with slight offsets due to the LWRE.

[14] We further examined the relationship between the SWRE and LWRE as a function of dust AOT called radiative efficiency by dividing the average bias adjusted DRE by the average dust AOT (Table 1). The mean shortwave efficiency (SW_{eff}) is -47.91 ± 3.81 Wm^{-2}/AOT and the longwave efficiency (LW_{eff}) is 8.96 ± 3.51 Wm^{-2}/AOT. In contrast *Li et al.* [2004] report a SW_{eff} value of -35 ± 3 Wm^{-2} although their study domain, period of study and methods are different than ours. Table 1 indicates that the SWRE is -7.75 ± 0.86 Wm^{-2} over all the years and the corresponding LWRE is 1.44 ± 0.57 Wm^{-2} with very low standard deviations. In comparison, *Yu et al.* [2006] report a SWRE mean value of -9.17 ± 2.13 Wm^{-2} from nine different observational-based methods for June–August over the tropical Atlantic. They also report mean SWRE values from five different numerical models to be -7.2 ± 2.73 Wm^{-2}. To our knowledge, LWRE values over the Atlantic Ocean are not available. Our results indicate that over the Atlantic Ocean, 20% of the SWRE is cancelled by the LWRE indicating the importance of dust aerosols in the thermal portion of the electromagnetic spectrum. It should be noted that DRE is calculated from pixels where $\tau_{0.55} > \tau_{ma}$. The dust DRE is only calculated when dust AOT > 0.0 and $f_{ma} < f < f_{an}$; thus, the dust only average is representative of a smaller set of pixels.

[15] While this approach is a measurement-based evaluation of dust aerosol effects on climate, there are several sources of uncertainty including instrument calibration ($\sim$0.8 Wm^{-2}), conversion of filtered to unfiltered radiances ($\sim$0.8 Wm^{-2}), angular dependence models ($\sim$0.25 Wm^{-2}), cloud contamination ($\sim$10%, or 0.3 Wm^{-2}), estimation of MODIS dust AOT (10–15%), and clear-sky flux estimations ($\sim$3%). Using the method described by *Zhang et al.* [2005b] our best estimates for the total uncertainties is $\pm$1.0 Wm^{-2}.

3. Summary

[16] Using 18 months of collocated CERES and MODIS data from six years (June–August, 2000–2005) over the Atlantic Ocean, we calculate both the cloud-free SWRE and LWRE of dust aerosols. Our results indicate that 20% of the SWRE is cancelled by the LWRE with a SW and LW radiative efficiency of -47.91 ± 3.81 Wm^{-2}/AOT and $+8.96 \pm 3.51$ Wm^{-2}/AOT respectively. Over source region such as deserts, due to the high surface albedos, the SWRE is usually small and difficult to estimate where as the LWRE could be significant [*Zhang and Christopher*, 2003] thereby further underscoring the thermal effects of dust aerosols. Currently there is no consensus on the anthropogenic fraction of dust aerosols and these values could range from 0–50% [*Tegen et al.*, 2004; *Mahowald et al.*, 2004]. However, if the tropospheric dust loading due to anthropogenic activities is indeed significant, then the thermal effects of dust aerosols could partially offset the shortwave radiative forcing of anthropogenic aerosols since anthropogenic aerosols due to their small particle sizes have negligible radiative effects in the thermal portion of the electromagnetic spectrum. This is the first multi-year assessment of the combined shortwave and longwave TOA radiative effects over the Atlantic Ocean and work is underway to extend this analysis over the global land and ocean areas.

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References

Bellouin, N., O. Boucher, J. Haywood, and M. S. Reddy (2005), Global estimate of aerosol direct radiative forcing from satellite measurements, *Nature*, *438*, 1138–1141, doi:10.1038/nature04348.

Cakmur, R. V., et al. (2006), Constraining the magnitude of the global dust cycle by minimizing the difference between a model and observations, *J. Geophys. Res.*, *111*, D06207, doi:10.1029/2005JD005791.

Christopher, S. A., J. Zhang, Y. J. Kaufman, and L. A. Remer (2006), Satellite-based assessment of top of atmosphere anthropogenic aerosol radiative forcing over cloud-free oceans, *Geophys. Res. Lett.*, *33*, L15816, doi:10.1029/2005GL025535.

Haywood, J., et al. (2003), Radiative properties and direct radiative effect of Saharan dust measured by the C-130 aircraft during SHADE: 1. Solar spectrum, *J. Geophys. Res.*, *108*(D18), 8577, doi:10.1029/2002JD002687.

Kaufman, Y. J., I. Koren, L. A. Remer, D. Tanre, P. Ginoux, and S. Fan (2005), Dust transport and deposition observed from the Terra-Moderate Resolution Imaging Spectroradiometer (MODIS) spacecraft over the Atlantic Ocean, *J. Geophys. Res.*, *110*, D10S12, doi:10.1029/2003JD004436.

Li, F., A. A. Vogelmann, and V. Ramanathan (2004), Saharan dust radiative forcing measured from space, *J. Clim.*, *17*, 2558–2571.

Loeb, N. G., and S. Kato (2002), Top-of-atmosphere direct radiative effect of aerosols from the Clouds and the Earth's Radiant Energy System Satellite instrument (CERES), *J. Clim.*, *15*, 1474–1484.

Mahowald, N. M., G. D. R. Rivera, and C. Luo (2004), Comment on "Relative importance of climate and land use in determining present and future global soil dust emissions" by I. Tegen et al., *Geophys. Res. Lett.*, *31*, L24105, doi:10.1029/2004GL021272.

Miller, R. L., et al. (2006), Mineral dust aerosols in the NASA Goddard Institute for Space Sciences ModelE atmospheric general circulation model, *J. Geophys. Res.*, *111*, D06208, doi:10.1029/2005JD005796.

Myhre, G., and F. Stordal (2001), Global sensitivity experiments of the radiative forcing due to mineral aerosols, *J. Geophys. Res.*, *106*(D16), 18,193–18,204.

Prospero, J. M., P. Ginoux, O. Torres, and S. Nicholson (2002), Environmental characterization of global sources of atmospheric soil dust derived from NIMBUS-7 TOMS absorbing aerosol product, *Rev. Geophys.*, *40*(1), 1002, doi:10.1029/2000RG000095.

Remer, L. A., and Y. J. Kaufman (2005), Aerosol effect on the distribution of solar radiation over the clear-sky global oceans derived from four years of MODIS retrievals, *Atmos. Chem. Phys. Disc.*, *5*, 5007–5038.

Tegen, I., M. Werner, S. P. Harrison, and K. E. Kohfeld (2004), Relative importance of climate and land use in determining present and future global soil dust emission, *Geophys. Res. Lett.*, *31*, L05105, doi:10.1029/2003GL019216.

Yu, H., et al. (2006), A review of measurement-based assessment of aerosol direct radiative effect and forcing, *Atmos. Chem. Phys.*, *6*, 613–666.

Zhang, J., and S. A. Christopher (2003), Longwave radiative forcing of Saharan dust aerosols estimated from MODIS, MISR, and CERES observations on Terra, *Geophys. Res. Lett.*, *30*(23), 2188, doi:10.1029/2003GL018479.

Zhang, J., S. A. Christopher, L. A. Remer, and Y. J. Kaufman (2005a), Shortwave aerosol radiative forcing over cloud-free oceans from Terra: 1. Angular models for aerosols, *J. Geophys. Res.*, *110*, D10S23, doi:10.1029/2004JD005008.

Zhang, J., S. A. Christopher, L. A. Remer, and Y. J. Kaufman (2005b), Shortwave aerosol radiative forcing over cloud-free oceans from Terra: 2. Seasonal and global distributions, *J. Geophys. Res.*, *110*, D10S24, doi:10.1029/2004JD005009.

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